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Net carbon dioxide emissions from alternative firewood-production systems in Australia

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Abstract

The use of firewood for domestic heating has the potential to reduce fossil-fuel use and associated CO_2 emissions. The level of possible reductions depends upon the extent to which firewood off-sets the use of fossil fuels, the efficiency with which wood is burnt, and use of fossil fuels for collection and transport of firewood. Plantations grown for firewood also have a cost of emissions associated with their establishment. Applying the FullCAM model and additional calculations, these factors were examined for various management scenarios under three contrasting firewood production systems (native woodland, sustainably managed native forest, and newly established plantations) in low-medium rainfall (600–800 mm) regions of south-eastern Australia. Estimates of carbon dioxide emissions per unit of heat energy produced for all scenarios were lower than for non-renewable energy sources (which generally emit about 0.3–1.0 kg CO_2 kWh^{-1}). Amongst the scenarios, emissions were greatest when wood was periodically collected from dead wood in woodlands (0.11 kg CO_2 kWh^{-1}), and was much lower when obtained from harvest residues and dead wood in native forests (<0.03 kg CO_2 kWh^{-1}). When wood was obtained from plantations established on previously cleared agricultural land, use of firewood led to carbon sequestration equivalent to −0.06 kg CO_2 kWh^{-1} for firewood obtained from a coppiced plantation, and −0.17 kg CO_2 kWh^{-1} for firewood collected from thinnings, slash and other residue in a plantation grown for sawlog production. An uncertainty analysis, where inputs and assumptions were varied in relation to a plausible range of management practices, identified the most important influencing factors and an expected range in predicted net amount of CO_2 emitted per unit of heat energy produced from burning firewood.

Keywords: Fullcam; Bioenergy; Carbon; Sensitivity; Sequestration; *Eucalyptus melliodora*; *Eucalyptus laevopinea*; *Eucalyptus cladocalyx*

1. Introduction

In Australia, between about 4.5 and 5.0 million tonnes of dry firewood are burnt annually (by 23% of households) for domestic purposes. About 72% of this wood is gathered from regions of low-medium rainfall (<800 mm) [1]. In Australia, firewood can be obtained from remnant woodlands, native forests, or plantations. Communities, forest growers and policy-makers are interested in effects of various firewood management systems on net greenhouse gas emissions. Non-renewable sources of energy such as natural gas, liquid petroleum gas (LPG) and electricity, produce between 0.3 and 1.0 kg CO_2 kWh^{-1} of energy produced [2]. The use of firewood for domestic heating may further reduce net carbon dioxide (CO_2) emissions, depending on the forest system and its management, fossil fuel use during tree establishment, harvest and transport operations, and on the degree of overall fossil-fuel substitution.

Our objective in this study was to estimate net CO_2 emissions for three contrasting systems producing firewood for domestic heating: (i) woodland; (ii) native forest harvested for wood production; and (iii) a newly

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established plantation. For each production system we quantified the effects of a range of management and harvesting practices. Due to its wide testing and calibration [3–6], the full carbon (C) accounting model FullCAM [7] was used to account for changes in C stocks (and the equivalent CO_2 emission) within living biomass, debris and wood products. Emissions of CO_2 associated with the establishment, harvesting and transport were estimated separately.

2. Methodology

2.1. Model description and defaults parameters

When applied for forest (as opposed to agricultural) systems, FullCAM uses CAMFor, an empirical C tracking sub-model which predicts net change in mass of C, usually on a monthly basis, in live tree biomass, debris, soil, and product pools for a given series of specified management regimes such as thinning and final harvesting (Fig. 1). CAMFor takes input data such as annual change in total stem volume or above-ground biomass, and then uses a series of parameters calibrated for specific species to estimate relative distribution of C in different tree biomass components at annual intervals; to calculate C concentrations in the different components, rates of turnover; and, finally, to calculate C in trees at the stand-level (Table 1).

In CAMFor, the debris of wood, bark, foliage, and fine and coarse roots are assumed to be consisting of two pools, decomposable and resistant, each sub-component having a specified breakdown rate characteristic of eucalypts [5] (Table 1). We assumed no change in soil C in this study because such change is generally small compared to changes in C within biomass and debris pools [3,8].

Decomposition rate of harvested products were used to estimate C stored in products such as sawlogs, mill residues and firewood, assumed to be 50% yr^{-1} for firewood, 2% yr^{-1} for sawn timber and 100% yr^{-1} for mill residues [9].

2.2. Production systems management regimes

We simulated three production systems (with three scenarios within each) within the 600–800 mm rainfall zone of south-eastern Australia over a 100-year period (Table 2). The first was woodland dominated by *Eucalyptus melliodora* (yellow box) where (i) no collection was compared with (ii) periodic (5 year) collection of fallen dead wood and (iii) annual collection of both dead fallen wood and dead standing trees. This species was chosen because it is one of the most common sources of firewood in Australia, with red box (*E. polyanthemos*) and yellow box supplying 0.54 million tones annually [1]. In south-eastern Australia, these species are already under extensive pressure from clearing land and agriculture and repeated harvesting for firewood is not sustainable. Communities are therefore encouraged to obtain firewood from less threatened forest types such as *E. laevopinea* (silvertop stringybark). Therefore, the second production system simulated was even aged native forests managed for sawlog production, dominated by *E. laevopinea*, where (i) no collection was compared with (ii) collection of harvest residues for firewood together with periodic (every 5 years) collection of fallen dead wood and (iii) collection of both harvest residues and the annual collection of dead fallen wood and dead standing trees. The third production system was establishment of a new plantation of *E. cladocalyx* (sugar gum) on ex-farmland (afforestation) (i) no collection was contrasted with (ii) the use of thinnings and harvest residues (from a plantation managed primarily for sawlogs) and (iii) a coppiced plantation grown solely for firewood production. This species was chosen because it can be grown in low rainfall regions and coppice prolifically. It produces strong and durable timber suitable

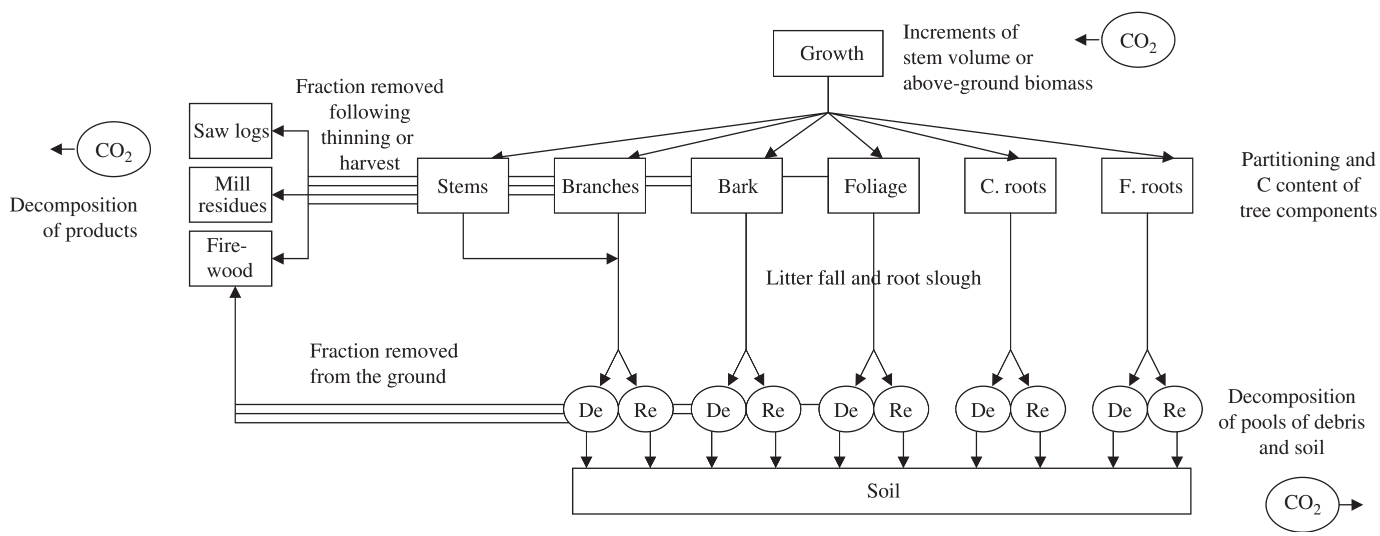

Fig. 1. Diagrammatic representation of FullCAM. De and Re represent the decomposable and resistant pools of debris, and C. roots and F. roots represent coarse and fine roots.

Table 1
Relative partition of biomass to tree components (expressed relative to partition of biomass to stem) for woodland, native forest and plantation production systems (based on a reviewed allometric relationships of *Eucalyptus globulus* by [34]), C contents (taken from [35,36]), and turnover rates of tree components, and the proportion of resistant components of debris material and their rates of breakdown and the under eucalypts (taken from [5,6])

	Stems	Branches	Bark	Foliage	C. roots	F. roots
Relative partition for woodlands	1.00	0.04	0.03	0.03	0.24	0.03
Relative partition for native forests	1.00	0.05	0.03	0.04	0.24	0.03
Relative partition for plantations[a]	1.00	0.35–0.00	0.16–0.12	0.21–0.00	0.30	0.20–0.02
C content (%)	52	47	49	52	49	46
Turnover (% yr^{-1})	NA	4.90	6.70	50.4	10.2	95.0
Resistant fraction (%)	100	100	100	80	100	62
Breakdown of resistant pool (% yr^{-1})[b]	12	12	20	30	20	30

[a]Relative partition of biomass to branches, bark and foliage components declines exponentially during the rotation. When coppiced, it was assumed that growth of coarse roots relative to the stem declined over the four coppiced rotations from 0.30 to 0.02.
[b]Decomposable pools were assumed to break down at rates of 100% yr^{-1}.

Table 2
Details of the three production systems, and their respective management scenarios, simulated using FullCAM

	Woodlands			Native forest			Plantation		
Species	*E. melliodora*			*E. laevopinea*			*E. cladocalyx*		
Region	Northern Tablelands, NSW			Northern Tablelands, NSW			Lismore, Victoria		
Annual rainfall (mm)	793			718			550		
Reference[a]	[10]			[10]			[20]		
Ave. age (yrs)	95			75			Varied		
Stem mortality (% yr^{-1})	0.7			0.2			0.0		
Basic wood density[b] ($t\,m^{-3}$)	0.792			0.649			0.758		
Initial conditions									
Above-ground biomass ($t\,C\,ha^{-1}$)	38.5			50.3			0.00		
Stem volume ($m^3\,ha^{-1}$)	78.0			134			0.00		
Debris ($t\,C\,ha^{-1}$)	15.0			35.7			0.00		
Management scenarios	1	2	3	1	2	3	1	2	3
Years between harvests	None	None	None	25	25	25	35	35	15
Logging[c]	None	None	None	Select.	Select.	Select.	Clearfell	Clearfell	Copp.
Thinning[d]	No	No	No	No	No	No	Yes	Yes	No
Firewood collection[e]									
Harvest trees	No	No	No	No	No	No	No	No	Yes
Slash	No	No	No	No	Yes	Yes	No	Yes	No
Material on the ground	No	Yes[+]	Yes[#]	No	Yes[+]	Yes[#]	No	Yes[+]	Yes[#]
Dead trees	No	No	Yes[#]	No	No	Yes[#]	No	No	No

Management scenarios are: (1) no firewood collection, (2) small-scale firewood collection, and (3) large-scale firewood collection.
[a]Reference detailing a site upon which case studies were based.
[b]Based on data from [10,16,37–39].
[c]Select: selective logging where 38% of the stems were removed at each logging event; Copp: three coppiced rotations, the stands being re-planted for the fourth rotation. Following coppicing, 40% of roots were assumed to have survived.
[d]It was assumed that 40% of stems were removed at age seven years, and another 50% removed at age 18 years.
[e]Where firewood was collected from either harvested trees, slash or from material on the ground, it was assumed that 80% of stem, branch and bark were available [+]every five years, or [#]every year.

for construction (Hamilton, L., Corangamite Farm Forestry Project, pers. com.) and is ranked as equal to yellow box, *E. melliodora* in terms of it's available heat output per unit volume [10a].

We assumed that woodland was naturally degrading (decreasing in live biomass over time) due to a high rate of tree mortality (0.7% yr^{-1}), with no replacement due to grazing stock, while the native forest was managed for saw log harvest, trees removed during a selective logging was limited to ensure the biomass stock recovered within 25 years. The assumed initial mass of live biomass and debris were determined from trial and error in order to simulate a system that was slowly degrading (woodlands) or in near-equilibrium conditions (native forest) (Table 2). It was assumed that the plantation was grown on ex-farmland, and had no initial live biomass or debris. Initial mass of products was assumed to be zero in all cases.

Following assumptions were made: (i) native forests and plantations were managed primarily for sawlog production with no market for pulp; (ii) 50% of the biomass of harvested stems remained on site as slash, 37% was lost as mill residues and 13% stored in sawlogs (F. Ximenes, State Forests of NSW, pers. com.); (iii) only firewood was removed from woodlands and coppiced plantations; (iv) firewood from either harvested trees (in coppiced plantations), slash from harvest operations in native forests and plantations, or from material on the ground, was 80% of available stem, branch and bark biomass.

2.3. Calculation of changes in stocks of C

2.3.1. Biomass of trees

Increments in stem volume or above-ground biomass were estimated from available information for all production systems, although assumptions were unavoidable. For woodlands, estimates of annual increments in stem volume were available for an open *E. melliodora* forest (age 73 years), and basal area was also measured at a nearby *E. melliodora* woodland site [10]. The ratio of basal areas between these two sites was used to calculate the increments in stem volume in the woodland from that measured in the open forest. We estimated that the current annual increment (CAI) for woodlands was initially $0.49\,m^3\,ha^{-1}\,yr^{-1}$, and declined to $0.23\,m^3\,ha^{-1}\,yr^{-1}$ after 100 years. Based on this, standing stem volume was $76\,m^3\,ha^{-1}$ for woodlands, equivalent to above-ground biomass of $73\,t\,DM\,ha^{-1}$ (Table 3). This is in the range of estimates for woodlands and scrubs across Australia ($42\,t\,DM\,ha^{-1}$, [11]), for eucalypts at woodlands sites in north-eastern Australia ($71\,t\,DM\,ha^{-1}$, [12]), and for black box woodlands in Victoria ($50\,t\,DM\,ha^{-1}$ [13]).

Based on the mean annual increment (MAI) for a *E. laevopinea* forests (of $3.2–3.7\,m^3\,ha^{-1}\,yr^{-1}$, at a mean age of 73 years [10]), and allowing for improvements in stand management, we assumed that the annual stem growth increment in the native forest was $3.4\,m^3\,ha^{-1}\,yr^{-1}$. Based on this value, and assumed density of stem wood (Table 2) and relative partitioning of biomass between tree components (Table 1), total above-ground biomass was predicted to be $156\,t\,DM\,ha^{-1}$ (Table 3), which was within the range of biomass of above-ground wood and bark ($119–297\,t\,DM\,ha^{-1}$) observed in a number of stringy bark forests from this region [10]. Predicted stem volume of $208\,m^3\,ha^{-1}$ (MAI of $2.77\,m^3\,ha^{-1}\,yr^{-1}$), were also comparable to the $211–594\,m^3\,ha^{-1}$ range in stem volumes, and MAI of $2.25\,m^3\,ha^{-1}\,yr^{-1}$, observed for blackbutt trees (*E. pilularis*) in the north coast of NSW [14,15].

A growth-curve (above-ground biomass) for *E. cladocalyx* plantations was determined from data for overstocked *E. cladocalyx* plantations in low (<500 mm) rainfall zones in western Victoria [16], with a low MAI of about $5.3\,m^3\,ha^{-1}\,yr^{-1}$. However, there is some evidence that for well-managed stands in regions where annual rainfall is at least 600 mm, MAI can be twice this amount [17,18, L. Hamilton,2003, pers. comm.]. Also, efforts are underway to improve the germplasm of *E. cladocalyx* (D. Bush, 2003, pers. comm.). Thus, assumed rates of growth were increased by a factor of 2.4, to produce a MAI equivalent to $13.0\,m^3\,ha^{-1}\,yr^{-1}$. With an assumed density of stem wood (Table 2) and relative partitioning of biomass (Table 1), above-ground biomass was $407\,t\,DM\,ha^{-1}$ and stem volume $456\,m^3\,ha^{-1}$ (Table 3). These estimates were generally consistent with the productivity measures provided by Theobald et al. [18] for an annual rainfall of about 625 mm in Victoria.

For the coppiced plantation, we assumed that growth rates were equivalent to those used for the sawlog plantation over the first rotation, growth rates would increase to 110% after the first coppice (since roots are

Table 3
Predicted stem volume, MAI, aboveground biomass, and mass of material on the ground (including fine litter and coarse woody debris) and in products during the 100-year simulation period for woodland, native forest and plantation

	Woodlands[a]			Native forest[b]			Plantation[b]		
Management scenarios	1	2	3	1	2	3	1	2	3
Biomass									
Stem volume ($m^3\,ha^{-1}$)	76	76	76	208	208	208	456	456	97.9
MAI ($m^3\,ha^{-1}\,yr^{-1}$)	0.80	0.80	0.80	2.77	2.77	2.77	13.0	13.0	6.25
Above-ground biomass ($t\,DM\,ha^{-1}$)	73.0	73.0	73.0	156	156	156	407	407	98.0
Debris									
Litter (pre-harvest) ($t\,DM\,ha^{-1}$)	13.4	7.16	3.06	14.3	10.0	3.84	44.5	23.2	11.9
Litter (post-harvest) ($t\,DM\,ha^{-1}$)	NA	NA	NA	40.7	10.3	9.37	278	55.5	20.6
Coarse wood (pre-harvest) ($t\,DM\,ha^{-1}$)	6.11	2.30	.0.49	5.36	2.36	0.42	25.8	4.91	4.40
Coarse wood (post-harvest) ($t\,DM\,ha^{-1}$)	NA	NA	NA	30.4	5.97	5.63	21.2	38.6	16.3
Products									
Sawlogs ($t\,DM\,ha^{-1}$)	0.00	0.00	0.00	28.0	28.0	28.0	97.3	97.3	0.00
Mill residues ($t\,DM\,ha^{-1}$)	0.00	0.00	0.00	78.3	78.3	78.3	276	276	0.00
Firewood ($t\,DM\,ha^{-1}$)	0.00	137	245	0.00	246	360	0.00	728	513

Management scenarios are: (1) no firewood collection, (2) small-scale firewood collection, and (3) large-scale firewood collection.
[a]Average over the 100-year simulation period.
[b]Maximum values predicted (i.e. prior to a harvest event).

already established), and then decline after the second and third coppice to 90% and 75%, respectively [19, D. Wildy, 2003, pers. comm.]. Average above-ground biomass production was predicted to be $98.0\,t\,DM\,ha^{-1}$, with a MAI of $6.5\,m^3\,ha^{-1}\,yr^{-1}$ (Table 3). This accords with the results of Holloway [20] who estimated that, for a coppiced plantation on a 15 year rotation in the 450–700 mm rainfall zone, about $100\,t\,DM\,ha^{-1}$ would be produced, which was equivalent to a MAI of about $8\,m^3\,ha^{-1}\,yr^{-1}$.

2.3.2. Debris

Using the default values taken from Paul and Polglase [5,6] for rates of turnover and decomposition of pools of debris (Table 1) we calculated that, in the absence of firewood collection, mass of litter (dead foliage, bark and woody material) under the woodland should average about $13.4\,t\,DM\,ha^{-1}$ (Table 3), which is within the range of 3.9 and $35.5\,t\,DM\,ha^{-1}$ measured for woodlands [21,22]. In native forest production systems not used for firewood collection, we predicted a mass of litter of $30.4\,t\,DM\,ha^{-1}$, in the range expected ($1.5–46.2\,t\,DM\,ha^{-1}$) for dry sclerophyll forests [22]. It was predicted that before harvest, mass of litter under plantations would accumulate to an average of $44.5\,t\,DM\,ha^{-1}$ in the absence of firewood collection, slightly greater than the range observed (2.7 and $39.4\,t\,DM\,ha^{-1}$) under eucalypt plantations grown in low rainfall regions [22,23].

2.3.3. Products

Sawlogs and mill residues were produced in native forest and the non-coppiced plantation case studies, and in these, the harvest index was 50%. In the native forests it was predicted that about $7.1\,t\,DM\,ha^{-1}$ of sawlogs were produced (and $20\,t\,DM\,ha^{-1}$ of mill residues) after each (25 year) selective harvesting, equating to a total production of about $28\,t\,DM\,ha^{-1}$ (and $78\,t\,DM\,ha^{-1}$ of mill residue) over 100 years (Table 3). Plantations grew more sawlog, $48.7\,t\,DM\,ha^{-1}$ (and $109\,t\,DM\,ha^{-1}$ of mill residues) after each harvest, and producing a total of $97\,t\,DM\,ha^{-1}$ (and $276\,t\,DM\,ha^{-1}$ of mill residue) over the 100 years.

The most firewood was predicted to come from plantations (up to $728\,t\,DM\,ha^{-1}$), and the least from woodlands (less than $245\,t\,DM\,ha^{-1}$) (Table 3). In woodlands and native forests, collecting firewood more regularly, and from dead standing trees as well as from coarse woody debris, increased the total mass collected by about 50–80%. Compared with collecting firewood from slash and other residues in plantations grown for sawlogs, about 42% less firewood was collected from plantations grown in shorter rotations coppiced for firewood production.

2.4. Calculation of CO_2 emissions from establishment, harvest and transport operations

Plantations require use of diesel fuel during establishment, e.g. for nursery maintenance, site preparation and planting of seedlings. Woodlands and native forests were already in existence. Carbon emissions associated with plantation establishment were based on energy costs prepared by Wells [24], reduced by 60% because his estimates included costs of clearing native forests whereas our scenarios was for establishment on agricultural land. Assuming a CO_2 conversion factor of $0.29\,kg\,CO_2\,kWh^{-1}$ for diesel fuel [25,26], we calculated that a total of $0.44\,t\,CO_2\,ha^{-1}$ was required for establishment of a new plantation, comprised of: $0.36\,t\,CO_2\,ha^{-1}$ for site preparation, and $0.04\,t\,CO_2\,ha^{-1}$ each for nursery maintenance and planting of seedlings.

Estimates of the amount of diesel consumed during harvest and transport depend on whether firewood is collected by private/small-scale collectors using chain saws, or by commercial operators using larger scale machinery. We assumed that the average basic wood density of green wood is $0.73\,t\,DM\,m^{-3}$, and that a total of $3.1\,kg\,CO_2\,L^{-1}$ is emitted from the production ($0.49\,kg\,CO_2\,L^{-1}$) and combustion ($2.66\,kg\,CO_2\,L^{-1}$) of diesel fuel [25–27]. Therefore, for small-scale operations where the one-way travel distance of firewood transport was about 100 km, and where $7.1\,L\,(t\,DM)^{-1}$ of diesel was used in harvest and $0.07\,L\,km^{-1}\,t^{-1}$ was used in transport (M. Hampson, 2003, pers. comm.), $68.1\,kg\,CO_2\,(t\,DM)^{-1}$ would be emitted from harvesting ($22.5\,kg\,CO_2\,(t\,DM)^{-1}$) and transport ($45.6\,kg\,CO_2\,(t\,DM)^{-1}$). In larger scale commercial operations in Australia, transport distance could be up to 400 km, resulting in a diesel requirement of $3.4\,L\,t^{-1}$ for harvest, $4.4\,L\,t^{-1}$ for cutting firewood into convenient size, and $0.02\,L\,km^{-1}\,t^{-1}$ for transport [27–31], emitting $51.7\,kg\,CO_2\,(t\,DM)^{-1}$ from harvesting ($10.3\,kg\,CO_2\,(t\,DM)^{-1}$) and transport ($41.4\,kg\,CO_2\,(t\,DM)^{-1}$). Such large-scale operations would be economical only where the quantity of firewood collected is great, such as when firewood is collected from plantations, or collected annually from native forests. Small-scale suppliers primarily collect their firewood from riverine forests and woodlands [1], and much of this wood may be used locally.

2.5. Calculation of net CO_2 emissions and conversion factors

The net amount of CO_2 emitted (as a result of changes in stocks of C as well as the use of diesel fuel) for per unit of energy generated from burning of firewood is termed the conversion factor ($kg\,CO_2\,kWh^{-1}$). This can be calculated for the burning of firewood for domestic heating:

$$\text{Conversion factor} = CO_{2\,\text{Net}}/(F \times E \times \varepsilon), \tag{1}$$

where F is the total mass of firewood available throughout the simulation period ($kg\,DM\,ha^{-1}$); E is the basic energy content of wood, taken as $5.28\,kWh\,(kg\,DM)^{-1}$ [32]; ε is the efficiency of typical domestic wood heaters, assumed to be 62% (although this may range between 10% and 70% depending on the type of wood heater used, [33]), and; $CO_{2\,\text{Net}}$ is the net emission of CO_2 over the 100 year accounting period ($kg\,CO_2\,ha^{-1}$).

The term $CO_{2\ Net}$ is calculated by adding the average annual change in stocks of C (assuming 1 t C equates to 3.667 t CO_2) over the 100-year simulation (or, in the case of plantations, the average accumulation observed during a rotation). It is the sum of changes in tree biomass ($CO_{2\ \Delta Biomass}$), debris ($CO_{2\ \Delta Debris}$), and harvested products ($CO_{2\ \Delta Products}$), and due to diesel usage during operations ($CO_{2\ Operations}$) such as the establishment of the trees and firewood harvest and transport:

$$CO_{2\ Net} = CO_{2\ \Delta Biomass} + CO_{2\ \Delta Debris} + CO_{2\ \Delta Products} + CO_{2\ Operations}. \quad (2)$$

2.6. Uncertainty analysis

All inputs and assumptions made in our scenarios have uncertainty in their value. We therefore used uncertainty analysis on the second of the management scenarios for each production system to investigate how expected variation in the value of important parameters influenced predicted CO_2 conversion factors (Table 4). We did not consider correlations between different inputs.

Table 4
Expected minimum and maximum values of inputs investigated in the uncertainty analysis

Input	Min. value	Default value	Max. value
Growth rates[a]	× 0.70	× 1.00	× 1.30
Mortality fraction[a]	× 0.30	× 1.00	× 1.70
Thinning fraction (% of stems thinned)[a]	−5	−0	+5
Logging frequency (years)[a]	−5	−0	+5
Rates of decomposition of debris (% yr^{-1})			
Stem wood	5	12	19
Bark	15	20	25
Foliage	25	30	35
Coarse roots	10	20	30
Fine roots	20	30	40
Collection of material from ground (%)	65	80	95
Recovery of products (%)			
Stem firewood	5	40	45
Stem slash	45	10	5
Branch firewood	10	80	90
Branch slash	90	20	10
Bark firewood	10	80	90
Bark slash	90	20	10
Rates of decomposition of products (% yr^{-1})			
Sawlogs	0.1	2	5
Mill residues	25	100	100
Firewood	25	50	100
Harvest efficiency (private, kg CO_2 (t DW)$^{-1}$)	48.1	68.1	88.1
Harvest efficiency (commercial, kg CO_2 (t DW)$^{-1}$)	31.7	51.7	71.7
Distance traveled (private, km)	50	100	800
Distance traveled (commercial, km)	50	400	800

[a]Because these values differ between case studies, for each case study the minimum and maximum values used in the uncertainty analysis were determined by adjusting the default value by a given percentage or value.

3. Results and discussion

3.1. Emission of CO_2 resulting from changes in stocks of C and diesel usage

3.1.1. Tree biomass

Woodland scenarios showed a net decline in live above-ground biomass (from 77 to 69 t DM ha^{-1}) over 100 years (Fig. 2(a)) because increments in C were insufficient to compensate for mortality. Losses were equivalent to 23.1 t CO_2 ha^{-1} (Fig. 3). Throughout the simulation period, the native forest system was assumed to be in near equilibrium (Fig. 2(b)), so that increases in C stocks were balanced by mortality, with a total loss of 3.92 t CO_2 ha^{-1} over the 100-year simulation period. In contrast, the new plantations accumulated large amounts of C, (Fig. 2(c)). This was equivalent to a net emission of −300 t CO_2 ha^{-1} (sequestration) after a 35-year rotation, or −83.2 t CO_2 ha^{-1} after a cycle of four coppiced rotations, after which the stand was re-planted.

3.1.2. Debris

Over the 100 year simulation period, tree mortality in the degrading woodlands (and to a lesser extent in the native forests), decreased the mass of C stored in the pools of debris, being 10.6 t CO_2 ha^{-1} in woodlands, and 2.03 t CO_2 ha^{-1} in native forests, without firewood collection (Fig. 3). Amounts of C in debris decreased even further with firewood collection, by 25.1–27.2 t CO_2 ha^{-1} in woodlands, and by 52.5–54.2 t CO_2 ha^{-1} in native forests. Therefore, in woodlands and native forests, emission of CO_2 from the pool of debris increased with increased firewood collection. In contrast, in plantations on agricultural land, predicted increase in storage of C in woody debris was equivalent to a net emission of −174 t CO_2 ha^{-1} without firewood collection, −84.4 t CO_2 ha^{-1} when firewood was removed from sawlog plantations, and −33.6 t CO_2 ha^{-1} in the shorter coppiced rotations grown for firewood production.

3.1.3. Products

Regardless of the management scenarios, predicted net emission of C in sawlogs was −27.1 t CO_2 ha^{-1} under native forests, and −33.7 t CO_2 ha^{-1} under plantations (Fig. 3). In all scenarios where firewood was collected, some remained unburnt by the end of the simulation period. The amounts were equivalent to a predicted net emission of between −0.11 for woodland and −28.6 t CO_2 ha^{-1} in native forests.

3.1.4. Establishment, harvest and transport operations

Based on data from Wells [24], we calculated that emission of 0.44 t CO_2 ha^{-1} for establishment of a new

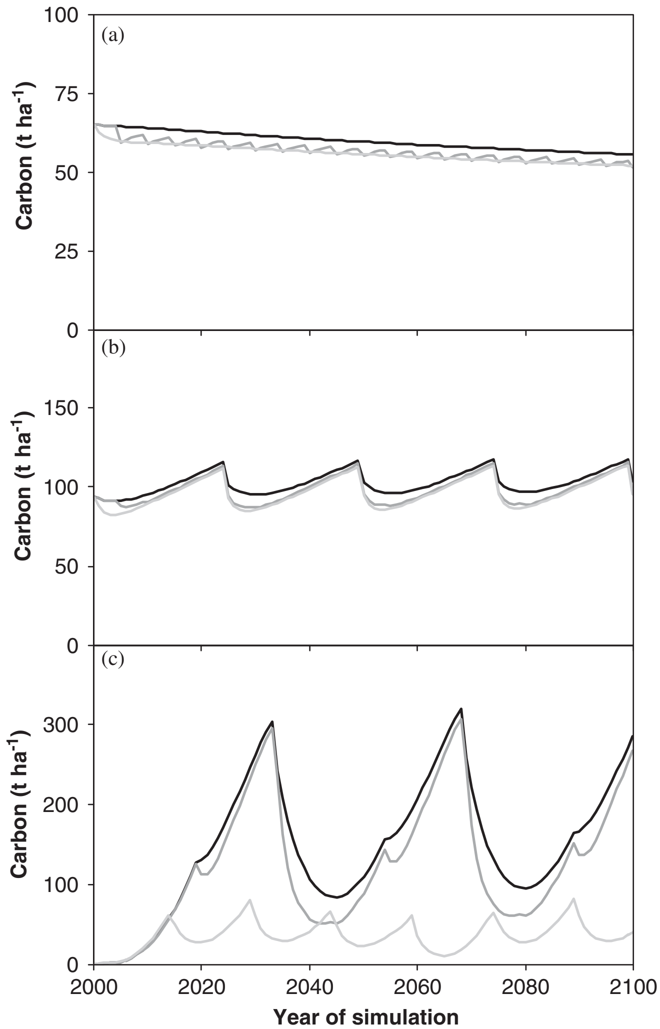

Fig. 2. Change in net C accumulation (resulting from changes in C within pools of biomass, debris and products) in the (a) woodland, (b) native forest and (c) plantation production systems where management scenarios are plotted in different shades: black, scenario one; dark gray, scenario two; light gray, scenario three.

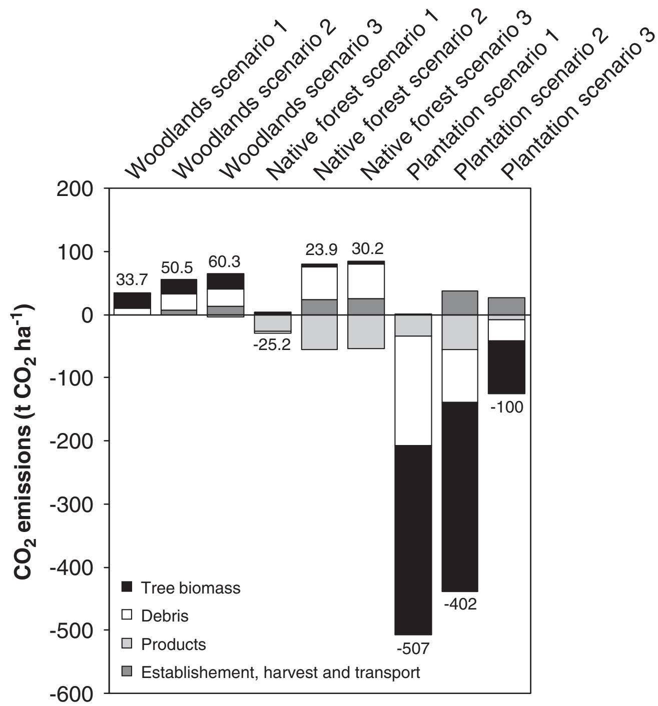

Fig. 3. Total emission of CO_2 from growth, decomposition of debris and products, and the establishment of trees and harvesting and transport of firewood. Emission of CO_2 resulting from changes in tree biomass, debris and products were estimated as the average annual change in C (expressed as net CO_2 equivalent emitted) multiplied by 100 years, or as the average accumulation of C during a 35-year rotation (plantation scenarios one and two), or during a 60-year cycle of four coppiced rotations (plantation scenario three).

plantation, and 68.1 kg CO_2 t^{-1} during small-scale firewood collections (where less than 250 t DM ha^{-1} of firewood was collected over the simulation period), and 51.7 kg CO_2 t^{-1} during larger operations. After taking into account the species-specific density of wood and the amount of firewood collected, emissions of CO_2 from the harvest and transport of firewood would be least from woodlands (<13.6 t CO_2 ha^{-1}), and most (up to 36.6 t CO_2 ha^{-1}) from plantations grown for sawlogs (Fig. 3).

3.2. Calculation of net CO_2 emissions and conversion factors

Developing a total budget for the C stored or released in biomass, debris, products, and diesel used in establishment, harvest and transport operations, we calculated that in the absence of firewood collection the net emission of CO_2 from a typical woodland in the Northern Tableland region for the 100-year simulation period was only 33.7 t CO_2 ha^{-1}, primarily due to tree mortality (Fig. 3). Collection and burning of firewood increases emissions of CO_2 in the short-term while decomposition of dead wood on the ground may take several decades. Therefore, harvesting 137 t DM ha^{-1} of firewood from woodlands resulted in a net emission of 50.5 t CO_2 ha^{-1} (or 0.11 kg CO_2 kWh^{-1}), while more intensive annual fuelwood collection, involving the harvesting of 245 t DM ha^{-1} of firewood resulted in a net emission of 60.3 t CO_2 ha^{-1} and an emission of only 0.06 kg CO_2 kWh^{-1} (Fig. 4). These results suggest that it is more efficient to collect firewood from both the ground and dead trees on an annual basis rather than collecting the dead wood on the ground once every 5 years, mainly because much of the potential firewood left on the ground will decompose anyway.

In native forest where firewood was not collected, there was a net emission of C equivalent to -25.2 t CO_2 ha^{-1} (sequestration) principally due to an increasing pool of wood products (Fig. 3). Harvesting firewood resulted in a net emission of between 23.9 and 30.2 t CO_2 ha^{-1} and 0.03 kg CO_2 kWh^{-1}, regardless of methods of collection. Clearly, burning this wood for domestic heating is likely to result in very little net emission of CO_2 per unit of energy generated.

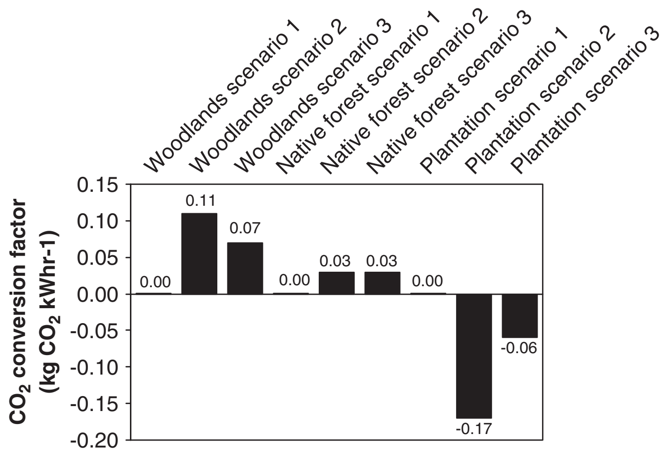

Fig. 4. Conversion factors of CO_2 calculated using the estimated net emission of CO_2 (resulting growth, decomposition of debris and products, and diesel use during the establishment of trees and harvesting and transport of firewood, Fig. 3), the amount of firewood available, basic energy content of wood and an assumed efficiency of wood heaters (Eq. (1)).

In the sawlog plantation, there was a net emission of C equivalent to $-507\,t\,CO_2\,ha^{-1}$; most of this sequestration (74%) resulting from the increase in live biomass. Collection and burning of firewood decreased net sequestration of C by an equivalent of $105\,t\,CO_2\,ha^{-1}$ as a result of accelerated release of CO_2 (Fig. 3). Where coppiced plantations were established for the purpose of firewood collection, there was a net emission of $-100\,t\,CO_2\,ha^{-1}$, again most of this (83%) being sequestered in live tree biomass. The CO_2 conversion factor was $-0.17\,kg\,CO_2\,kWh^{-1}$ when firewood from sawlog plantations was burnt, and only $-0.06\,kg\,CO_2\,kWh^{-1}$ for burning firewood from coppiced plantations. Therefore, there was a much greater benefit from collecting firewood from thinnings and residues remaining from harvest in a sawlog plantation rather than from harvesting coppiced trees grown for the purpose of firewood production. This was because the increase in storage of C in biomass and debris was almost four times as great in the plantations grown on the longer rotations (Fig. 2).

Our results indicate that in terms of limiting net CO_2 emissions, firewood is generally more favorable for domestic heating in Australia than non-renewable sources of energy such as natural gas, LPG and electricity produced by coal (that have conversion efficiencies of $0.31–1.00\,kg\,CO_2\,kWh^{-1}$, [2]). There are few additional emissions associated with the production and collection of firewood, particularly when firewood is collected from thinnings, slash and other residues of a commercially grown plantation.

3.3. Uncertainty analysis

Assuming a basic energy content of wood of $5.28\,kWh\,kg^{-1}$ DM, and a wood heater efficiency of 62%, the calculated conversion factor of CO_2 reflects the net emission of CO_2 relative to the amount of firewood available for burning (Eq. (1)). Therefore, growth rates and mortality of trees were important determinants of conversion factors in woodland and native forests since they affected emission of CO_2 (stocks of C in biomass and debris) to a greater extent than amounts of firewood that was available (Fig. 5). Partitioning of C to branches in these mature trees was relatively small as were turnover rates ($<5\%\,yr^{-1}$) (Table 1). Thus, any change in growth rates were predicted to have only marginal effect on the amount of dead wood available for collection on the ground. In contrast, in plantations where firewood was obtained mainly from thinning and harvest residues, the amount of firewood available was more directly related to tree growth rates. Therefore, increasing growth rates increased both predicted net emission of CO_2 and firewood availability equally, and thereby had little effect on CO_2 conversion factors.

The most important factors influencing CO_2 conversion factors in plantations were the recovery of products (how much material harvested was assumed to be left on-site, or used for saw-log production as opposed to firewood production), and frequency of harvest, since these had a particularly large influence on the amount of firewood available. In all production systems, other factors such as transport distances, efficiency with which firewood was harvested, and the fraction of material collected from the ground, were less important in terms of their effect on conversion factors.

The uncertainty analysis provided a range in expected conversion factors for CO_2 given the uncertainty in our assumptions and model inputs. These results demonstrated that when we assume a wood heater efficiency of 62%, no matter where firewood was obtained, the use of firewood for domestic heating resulted in conversion factors that were much less than that obtained from non-renewable energy sources of fuel ($0.3–1.0\,kg\,CO_2\,kWh^{-1}$) even given the uncertainty in some of the input values. However, the efficiency of wood heaters can vary between 10% and 70% depending on the type of heater [33]. With efficiencies less than 20%, as might apply for some open fire places, sourcing firewood from woodlands may not always be better than using non-renewable sources of energy for domestic heating. This, together with the fact that in Australia, many remnant woodlands are degrading and losing biodiversity, suggests that harvest residues from native forest or plantations should be the preferred over woodlands as a source of firewood.

4. Conclusions

This analysis indicated that the use of firewood for domestic heating has lower net CO_2 emissions than non-renewable energy sources such as gas and electricity, particularly when firewood is collected from thinnings, slash and other residues of commercially grown plantations. Regardless of the efficiency of wood heaters used,

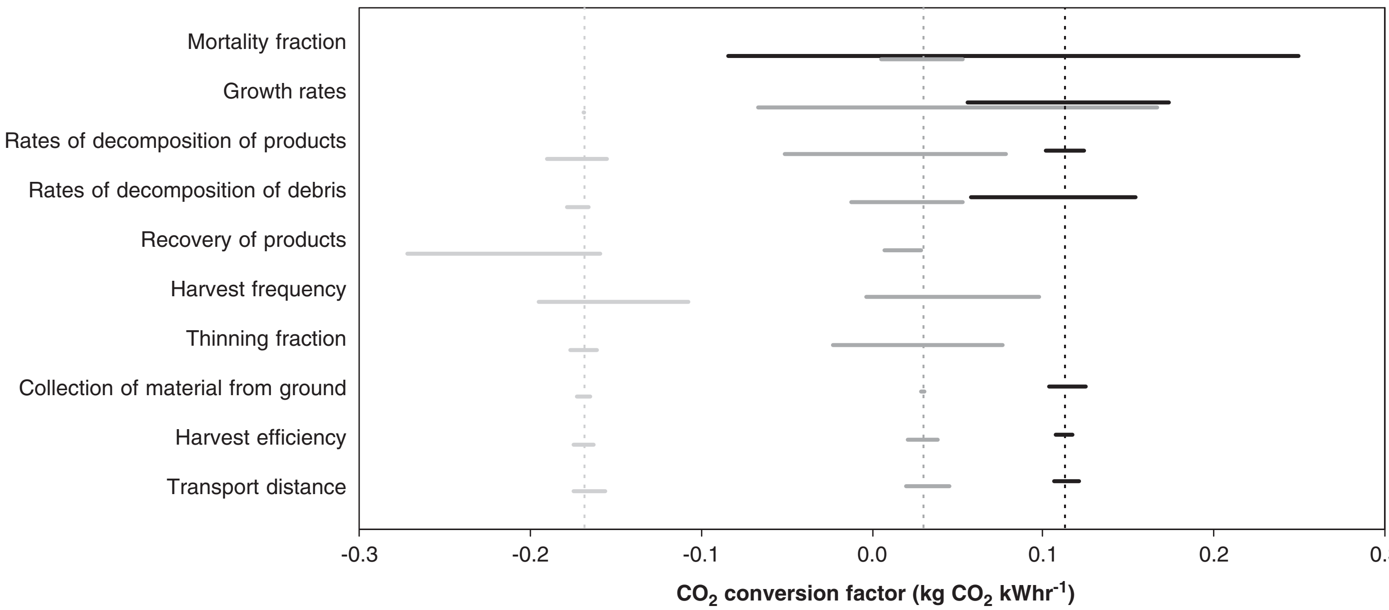

Fig. 5. Calculated CO_2 conversion factors as a result of the burning of firewood collected from management scenario two of woodland (black), native forest (dark gray) or plantation (light gray) systems when key input values are varied between the minimum and maximum value expected (Table 4). Dotted lines indicate default values for the given production system.

collection of firewood from coppiced plantations, or from the harvest residues of native forests, was also favorable. If wood collected from woodlands is burnt in heaters with low efficiencies ($<20\%$), it is likely that more CO_2 will be emitted per unit of heat energy generated from burning this wood than when using the more efficient alternative, non-renewable energy sources. Furthermore, leaving dead wood and trees as habitat in remaining woodlands may help preserve biodiversity in some ecosystems.

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